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A framework for medium-fidelity wake dynamics in moderately complex terrain

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A framework for medium-fidelity wake dynamics in moderately complex terrain

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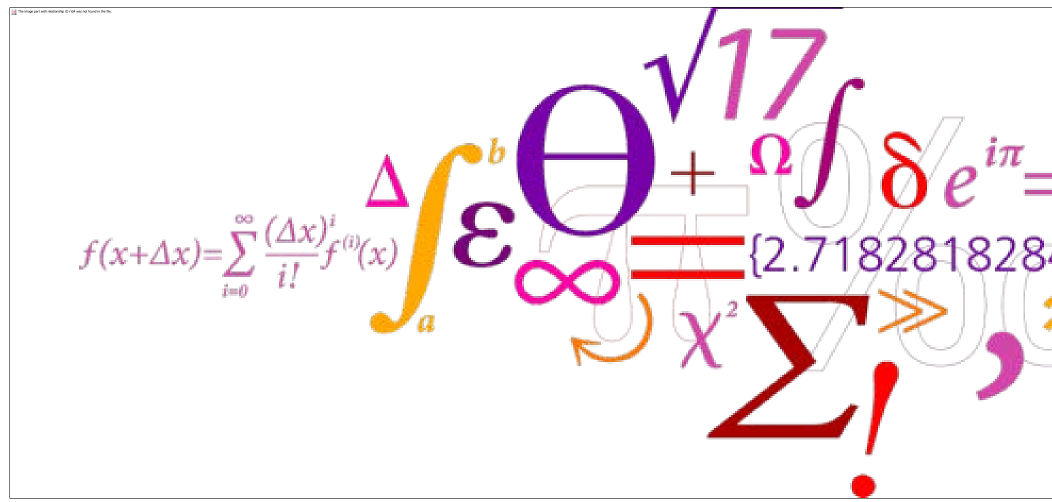

DTU Wind Energy
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Outline

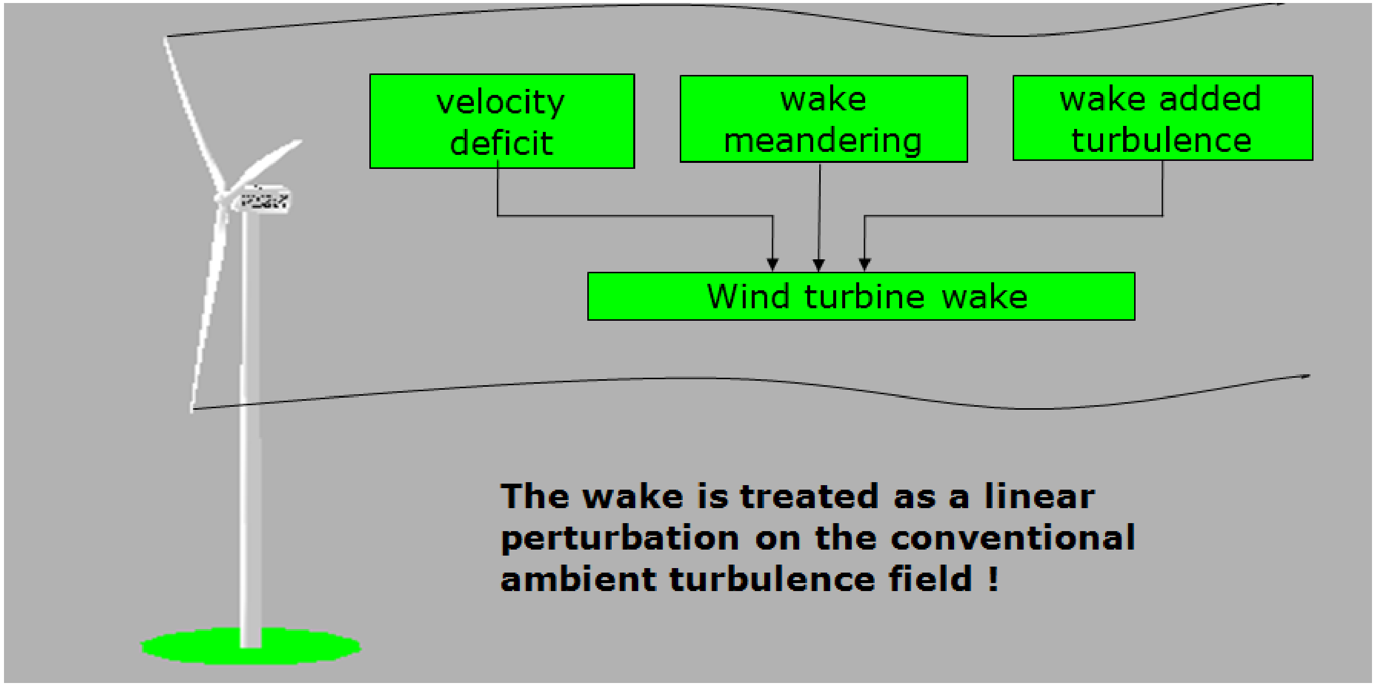
- Motivation
- DWM “classic” for flat terrain
- Generalization of DWM to “moderately” complex terrain
  - Definition of “moderately” complex terrain
  - Wake down-stream advection path
  - Wake deficit in MFoR
  - Wake down-stream advection velocity
  - Stochastic wake meandering
  - Fast computation of stream lines and speed up in “moderately” complex terrain
- Conclusions
- Future work

Motivation

- *Non-stationary* flow fields are required for WT load estimation, facilitates WT power production estimation ... and thus WF topology optimization
- High-fidelity CFD-LES modeling is CPU-costly ... and a coupled aeroelastic/CFD-LES approach is **not** feasible for a large number of WF simulations!
- Need for medium-fidelity flow field models that
  - Preserves the essential physics of non-stationary wake flows
  - Is (relatively) in-expensive
  - Allow for a straight forward coupling with aeroelastic models

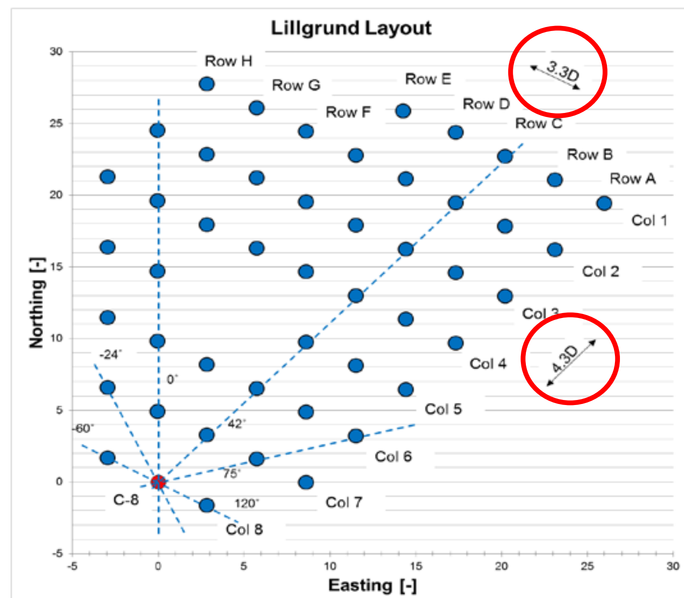
DWM “classic” (1)

- Included in the IEC-code as recommended practice
- Flat and homogeneous terrain (streamlines,turbulence)
- “Poor man’s LES” ... based on a passive tracer analogy
  [Larsen GC et al.; Wake meandering – a pragmatic approach; WE]



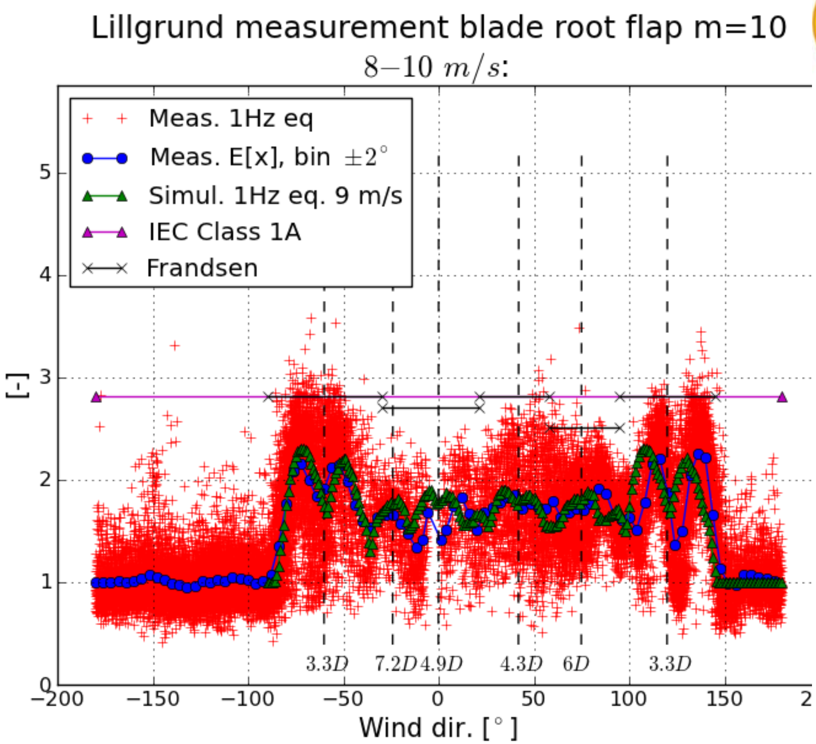
DWM “classic” (2) – does it work?

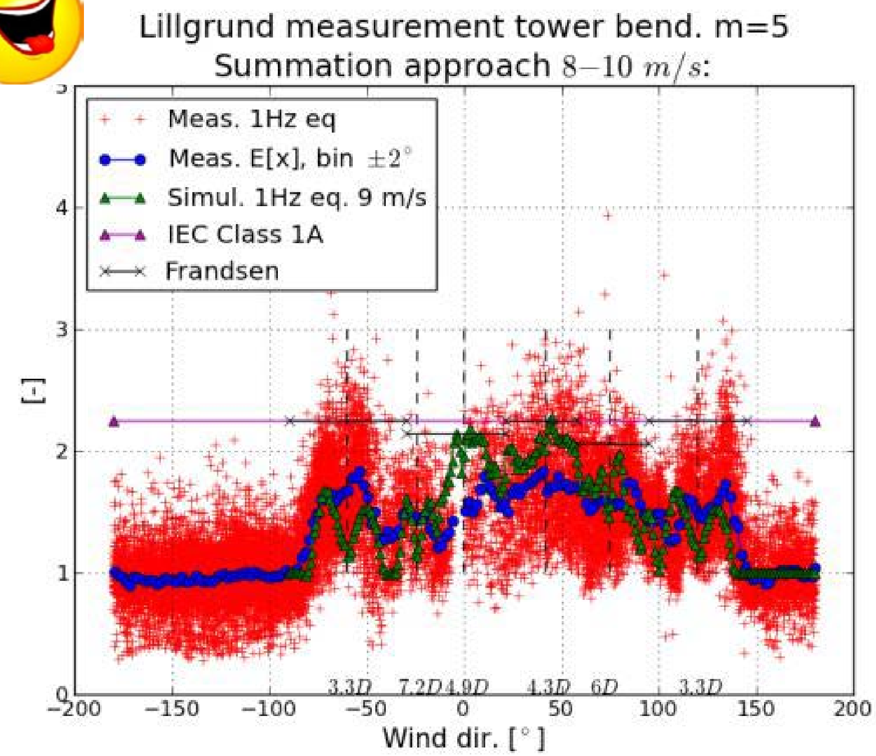
- 48 SWT 2.3 MW PRVS turbines
- Lowest spacing is 3.3D
- Turbine C-8 is fully instrumented with strain gauges … blade and tower bending moments are available



DWM “classic” (3) – does it work?

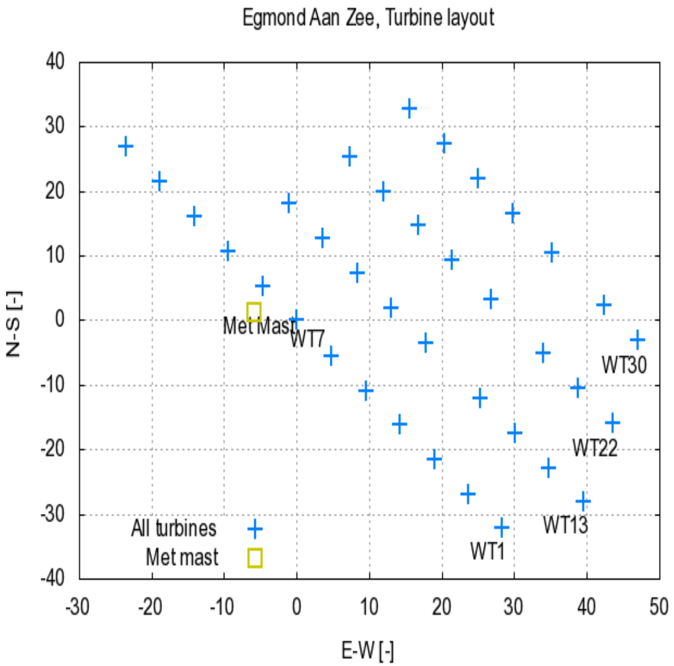
- Flap and tower bottom fatigue equivalent moments
  - 9m/s [Larsen TJ et al.; EWEC 2015]

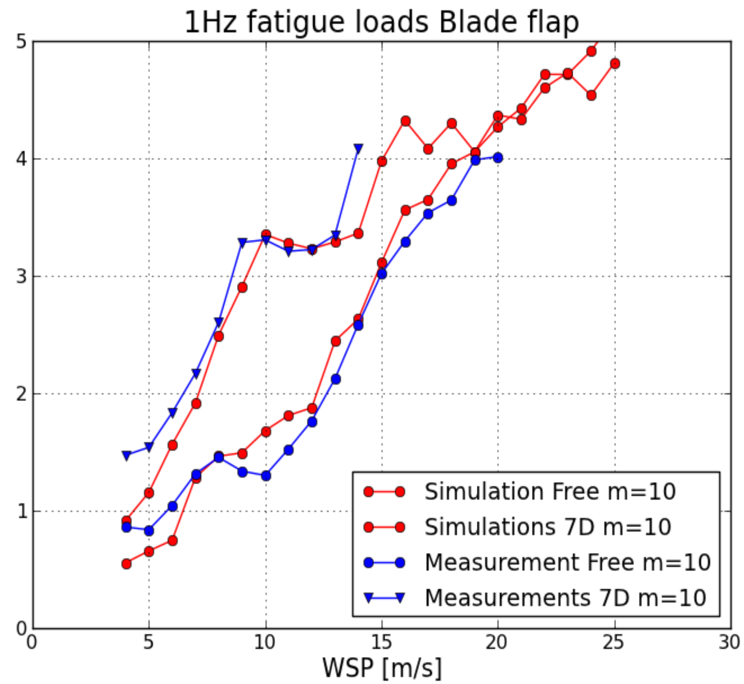




DWM “classic” (4) – does it work?

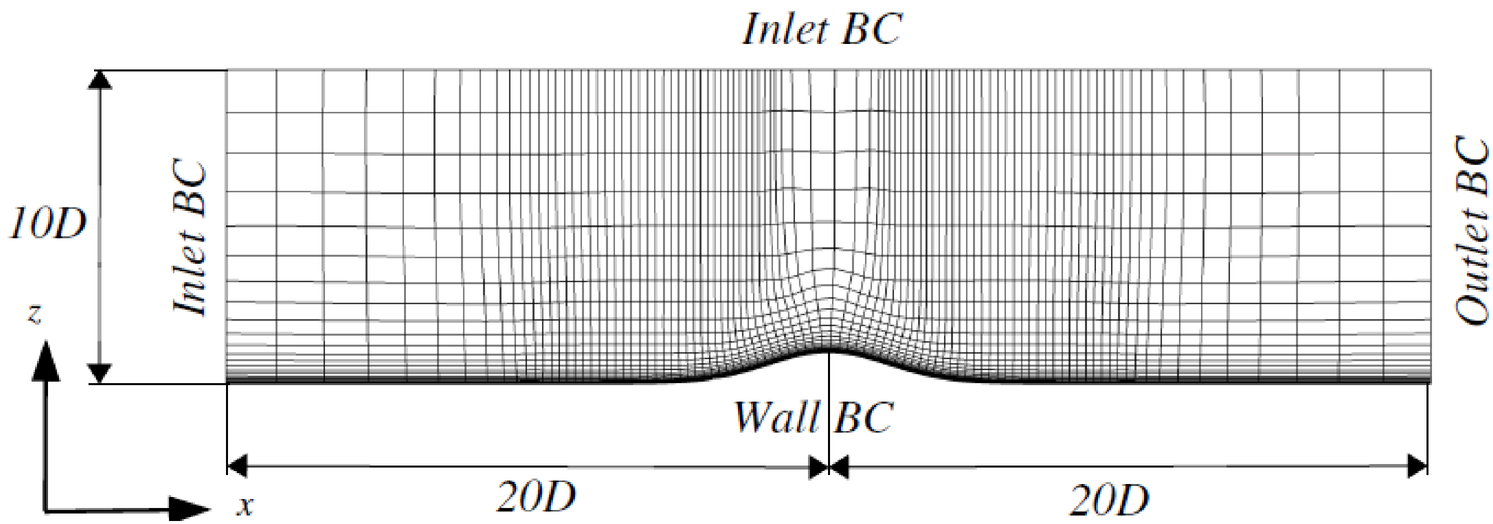
- Egmond Aan Zee - a farm of 36 Vestas 3MW V90 turbines
- Load and production compared for WT7 in free sector and full wake sector (~315deg)





Generalization of DWM – “complex” terrain (1)

- “Moderately” complex terrain defined as orographics with no re-circulation ... in terms of critical gradient
- 2D Gaussian hill + EllipSys3D RANS simulations
- Separation occurs if the skin friction coefficient becomes negative



- 384 and 128 cell are used in the horizontal and vertical dimension ... grid independent results

Generalization of DWM – “complex” terrain (2)

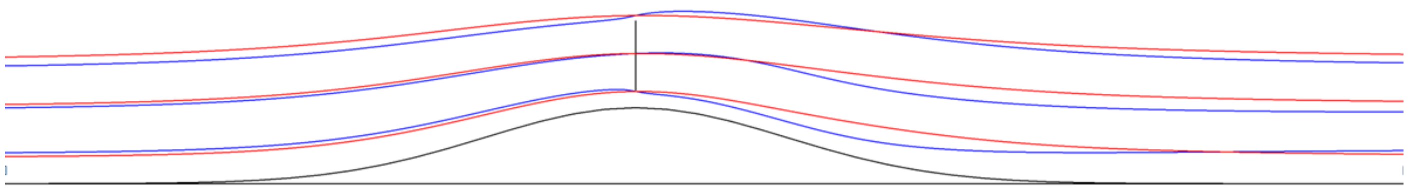
- Separation on the Gaussian hill is investigated for:
  - Different slope angles ... (16° - 21°)
  - 8.0 m/s ... and neutral logarithmic profile
  - Three roughness lengths ... (1 m, 0.1 m and 0.03)
  - Two turbulence models ... (k- ε and k-ε-f_P)

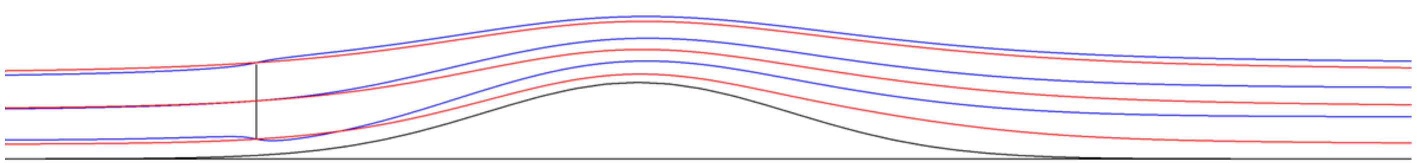
Turbulence model	$z_0 = 0.03$ m	$z_0 = 0.1$ m	$z_0 = 1.0$ m
k-ε	21°	19°	17°
k-ε-f_P	20°	18°	17°

- Critical gradient in this context defined as 17°
  [...other studies have come to a similar result – e.g. WAsP CFD]

Wake downstream advection (1)

- Stream lines (17°) ... blue wake affected; red no wake





Wake downstream advection (2)

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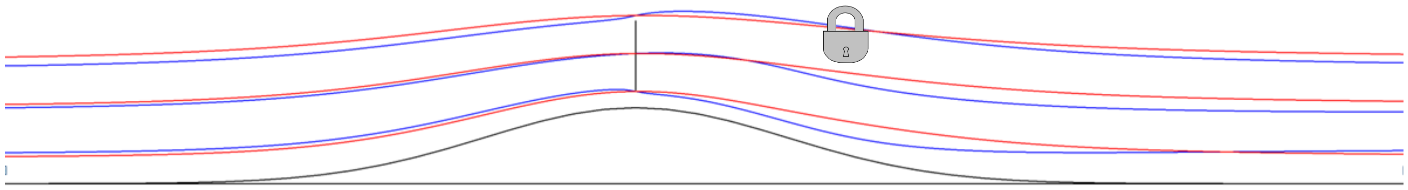
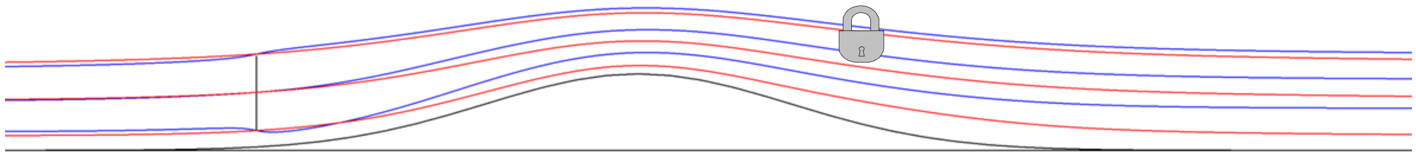
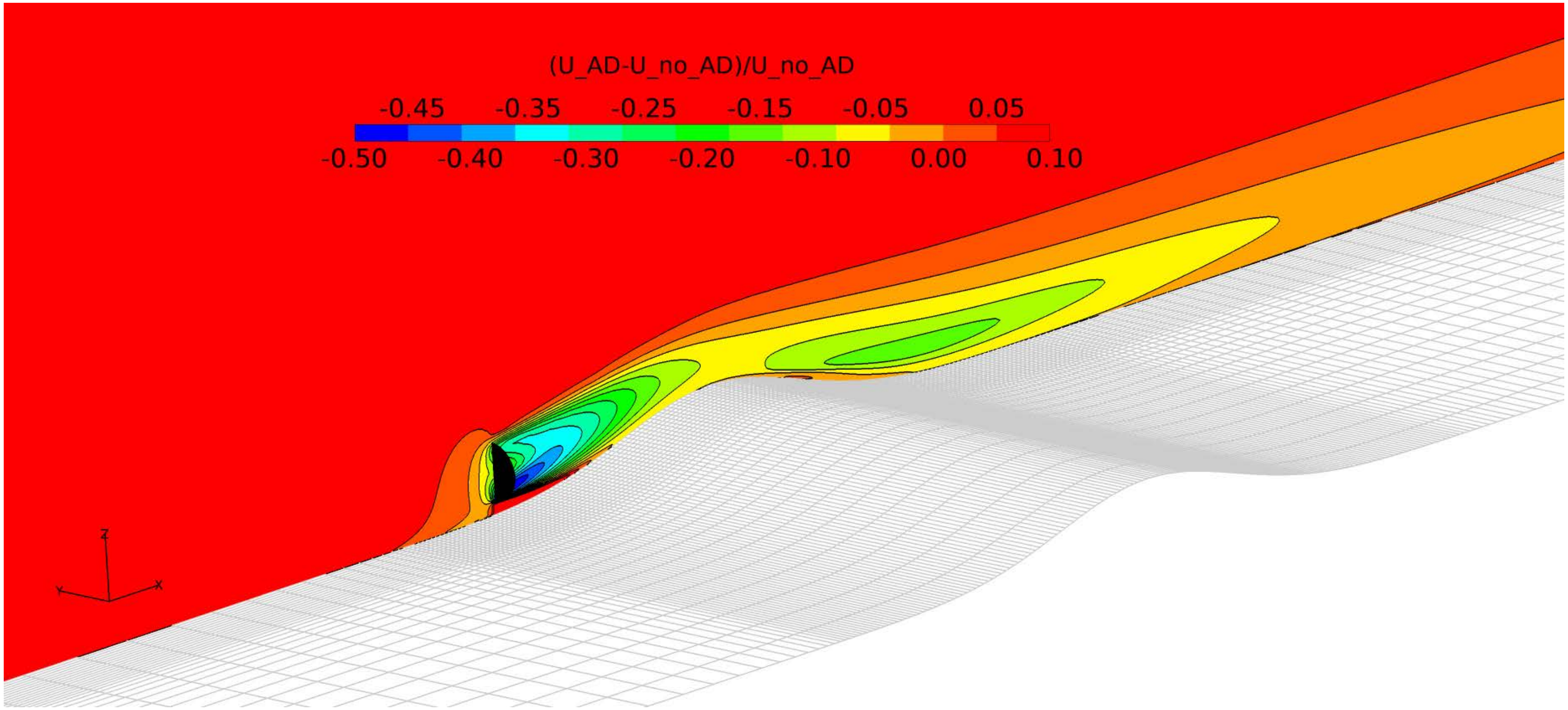




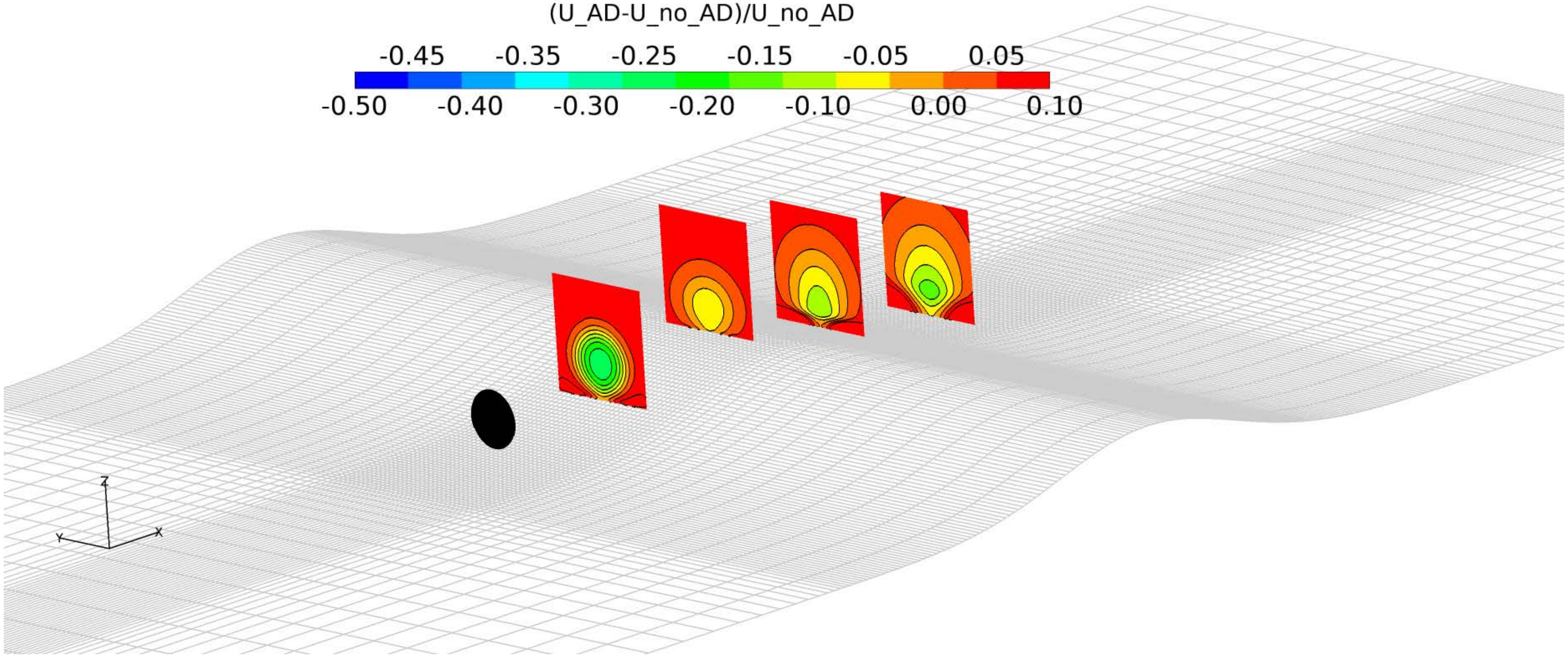
- 1’st conjecture: In the vicinity of the hill, the highest altitude stream line match the best!

Wake deficit in MFoR (1)



- Wake "follows" the hill in curve-linear coordinates ... as also indicated by the stream-line analysis
- NOT true for separated flows!

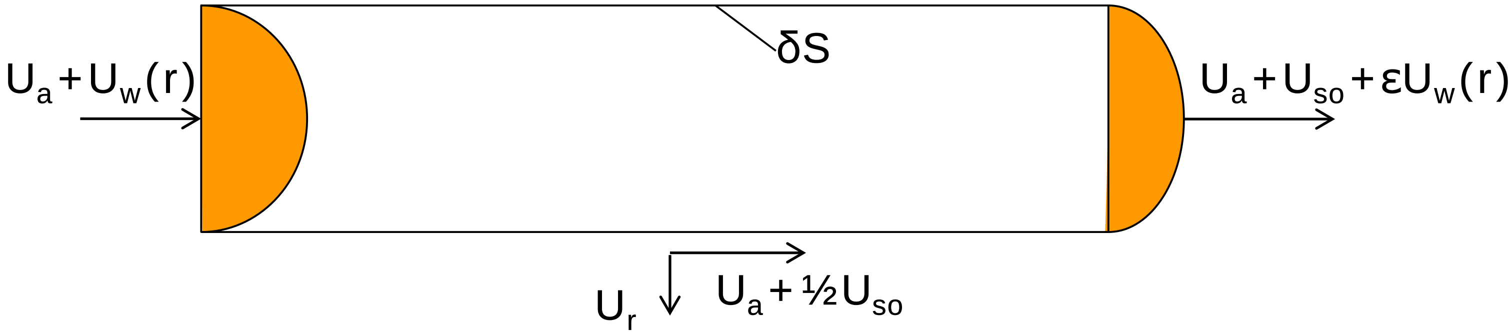
Wake deficit in MFoR (2)



- 2’nd conjecture: Wake expansion is not significantly affected by hill speedup “=>”
- 3’rd conjecture: Wake deficit scales under a similarity presumption

Wake deficit in MFoR (3)

- Wake deficit scales under a similarity presumption: $U_{w,speedup}(r) = \varepsilon U_{w,ambient}(r)$
- The similarity assumption is restricted to the dominating along wind wake component



- Continuity equation yields $\int_{\delta S} U_r dS$ as function of the (idealized) along wind velocity components

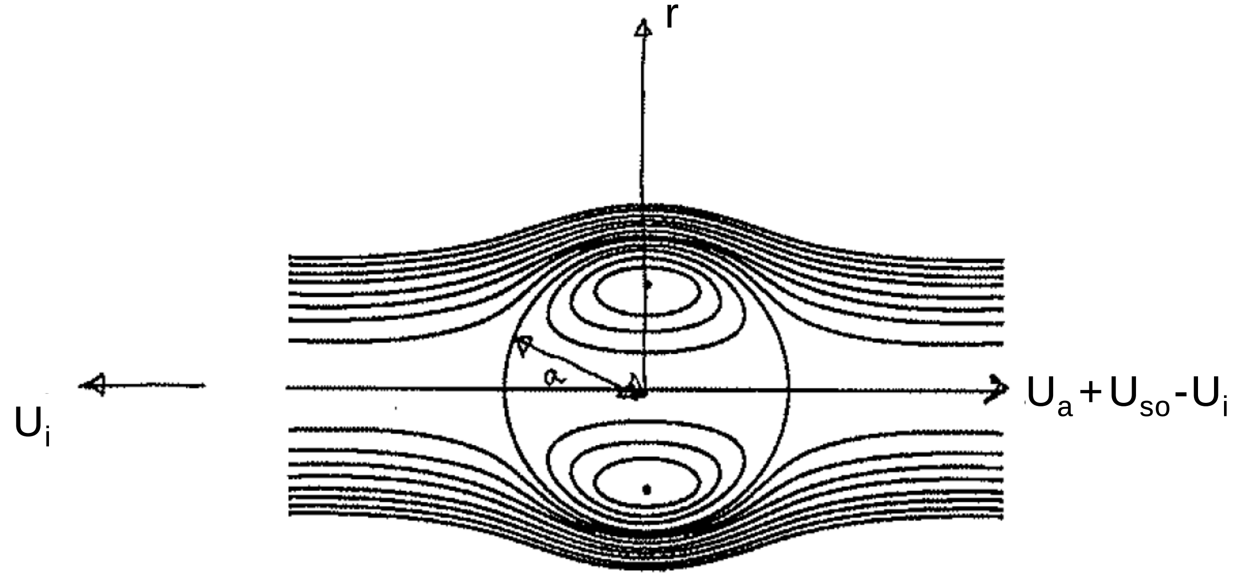
Wake deficit in MFoR (4)

- Momentum flux in the mean flow direction pr. unit time across the surface of the control volume yields:

  $\varepsilon = f(U_a, U_{so}, U_w)$ ... a simple algebraic expression

Wake downstream advection velocity

- 4'th conjecture: Advection based on a Hill's vortex approach and a rotor averaged wind speed (U_a+U_{so}) ... in the relevant flow domain [Lamp, 1932]



- $U_{adv}= U_a+U_{so}-U_i=U_a+U_{so}-0.4\varepsilon U_w(0)$ .. along streamline

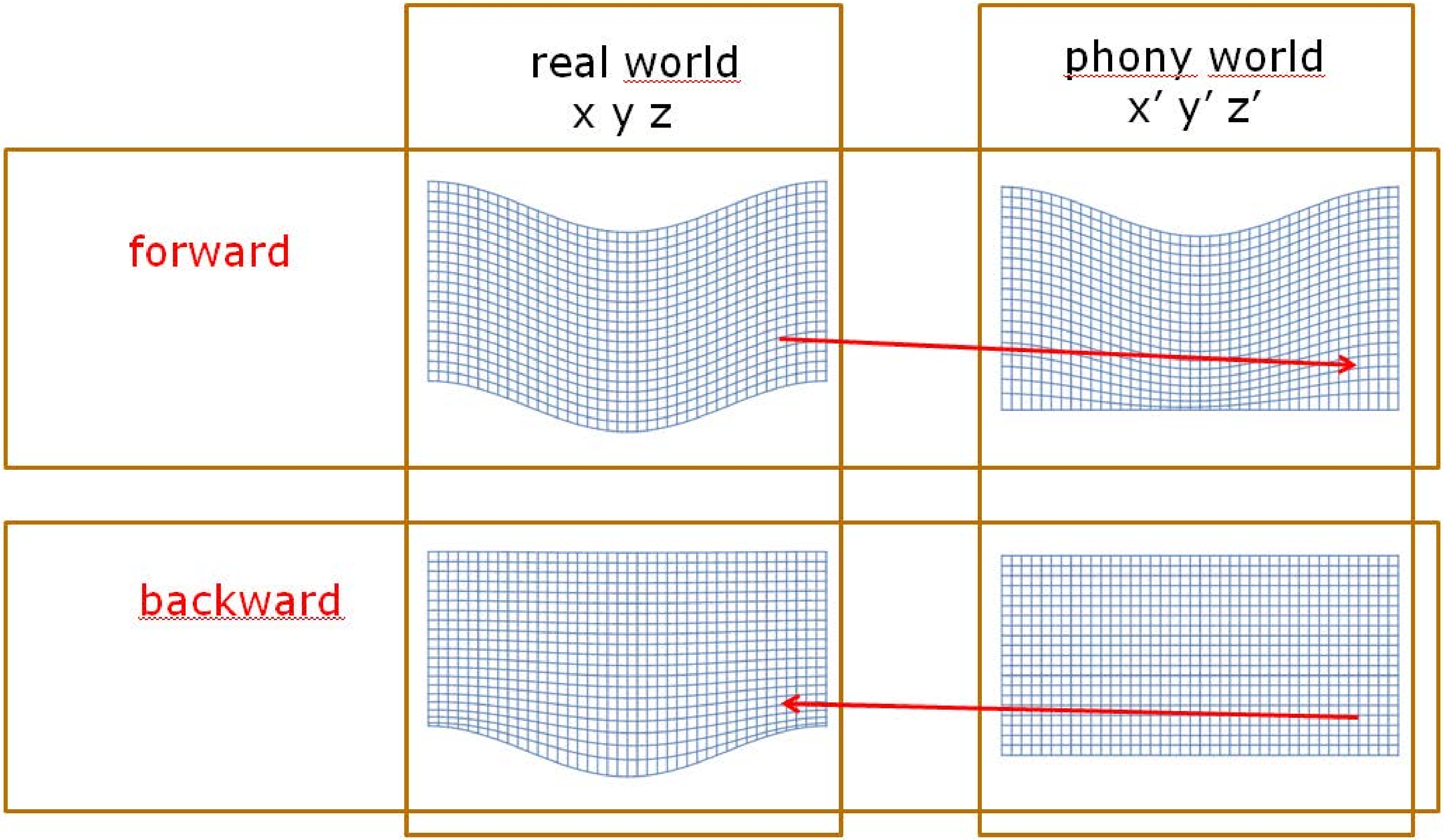
Stochastic wake meandering

- Wake meandering (laterally, vertically) around streamline driven by large scale ABL turbulence ... cut off frequency U/2D
- 5'th conjecture: Conventional anisotropic ABL turbulence for flat terrain can be used ... expressed in a Cartesian frame of reference
- Mann spectral tensor used for neutral conditions
- A generalized spectral tensor used for non-neutral conditions ... consistently including buoyancy effects

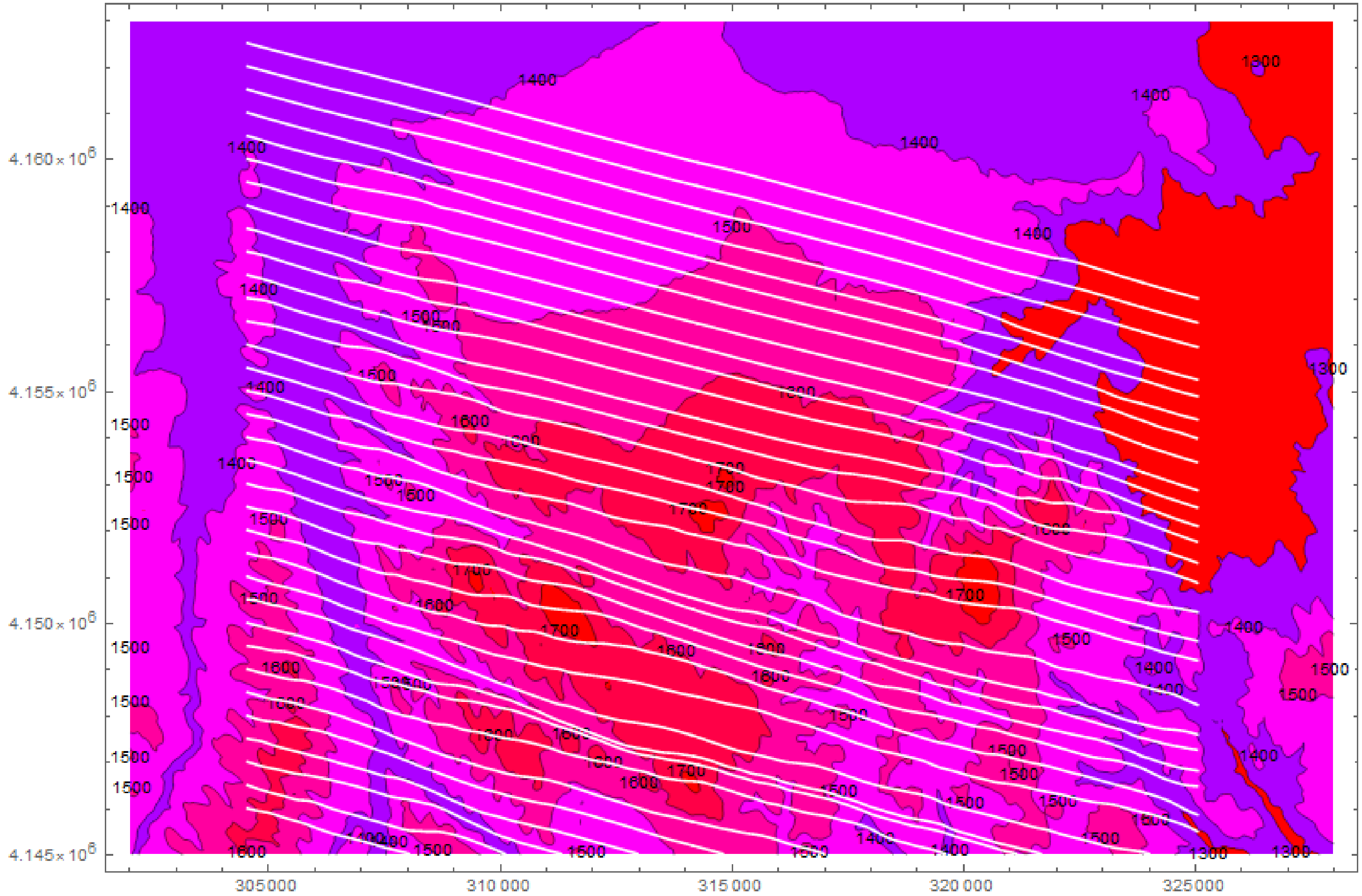
Fast computation of streamlines and speedup (1)

- Fuga “classic”:
  - Linearised CFD RANS code formulated in mixed spectral domain
  - Appr. 1.000.000 times faster than conventional (non-linear) CFD RANS
  - No numerical diffusion
- Fuga adapted to “moderately” complex terrain:
  - Only the linearized equations (first order perturbation in Cartesian terrain height *h*) have been considered
  - The trick is to transform to a phony, flat world - using a phony farm layout ... and perform computations here
  - The phony streamlines are completely straight, but they will follow the hills when transformed back to the physical world

Fast computation of streamlines and speedup (2)



Fast computation of streamlines and speedup (3)



Conclusions

- Framework for medium-fidelity wake dynamics in “moderately” complex terrain formulated ... as based on five simplifying conjectures
- Fast computation of streamlines and speedup facilitated using a linearized RANS model ... adapted to “moderately” complex terrain using first order perturbation theory

Future work

- Quantify the extension of the speed-up regime!
- The present streamline analysis is planned to be extended from a 2D Gaussian hill to a 3D Gaussian hill ... and for more wind speeds
- Present offshore-like WT replaced by a higher WT
- Turbulence in complex terrain may be spatially inhomogeneous ... which should be investigated
- ABL stability may have a role in definition of "moderately" complex terrain/re-circulation ... this should be checked

Acknowledgements

The EUDP project “Optimized layouts for wind farms in complex terrain - FARMOPT”, under contract 64013-0405, is acknowledged for financial support and thus for making this study possible